Identification of Missing Objects with Group Coding of RF tags

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***Abstract*—Physical objects often form a group such as objects in a shipping container. RFID enables us to identify each object and even the container itself. However, current RFID does not provide information on IDs missing from a group. This paper proposes a method to determine the unique IDs of objects missing from a group without any external database or verifier. The proposed method logically splits a group into mutually overlapped sub-groups and writes group-related information, which is generated from the unique IDs of objects in the sub-group, to RF tags' memory. When we check the integrity of a group of objects, unique IDs and group-related information of RF tags are extracted from RF tags' memory. With an iterative decoding over group-related information with the unique IDs of identified objects, missing IDs are determined. A numerical simulation reveals that the proposed method can identify 96-bit unique IDs of up to 64 objects missing from a group composed of 100 objects by writing 840-bit group-related information to each RF tag. We also examined the performance with an experiment and confirmed that we can successfully determine 16-bit IDs of up to 12 missing RF tags from a group of 20 RF tags by writing 280-bit group-related information to each RF tag. The experiment results agree well with the numerical simulation.**

I. Introduction

RFID, radio frequency identification, is an automatic identification technology which is composed of RF tags, interrogator and associated information system. Because an interrogator collects RF tags' information via RF communication, RFID can identify not only line-of-sight objects but also non-line-of-sight objects. With RF multiple access technique, RFID can identify many objects swiftly. We also can write data to each RF tag's memory. These features make RFID different from other existing automatic identification technologies such as bar-code.

Real-space objects often form a group, and verification of the integrity of such group of objects is required. Objects in a shipping container are typical practice of a group. RFID identifies individual objects in the container and even the container itself. RFID readings, however, cannot let us know if there is any missing object from the container during the transportation. Such group integrity check is usually done by looking up the shipment list in EDI (Electric Data Exchange). As such, in an off-line (no network) environment, the integrity check needs to be done manually. Even in an on-line environment, it is not rare that RFID and EDI system do not automatically interact so that the integrity check slows down the whole business process.

There are some related works on the verification of the integrity of a group of objects. Yoking proof [1] introduced by Juels confirms the integrity of a group of RF tags by exchanging a message authentication code between RF tags and a verifier. There are some researches ([2], [3], [4], [5], [6]) which improve yoking proof. Inoue [7] proposed a systematical scheme which detects a read failure from the results of reading of grouped RF tags by multiple readers. Potdar [8] proposed an integrity-check method which uses the total weight of grouped objects in addition to reading results of RFID.

We see the similarity between this group verification problem and the packet-level forward error correction ([9], [10], [11], [12]). When we treat the inventoried ID of an object as a packet, the missing of objects can be treated as the packet loss in an erasure communication channel. We proposed "group coding" of RF tags [13] which can check the integrity of grouped RF tags by splitting the group into overlapped sub-groups and writing group-related information to the memory of RF tags attached on the objects. We can also determine the number of missing objects, if any, by the group coding.

We received strong supports from the industry on the group coding. Although the group coding, which enables us the determination of number of missing objects, is appreciated, almost all of the industries require the identification of missing IDs. The above-mentioned group coding method, which determines the number of missing objects, is simple and easily-computed, but cannot determine the missing unique IDs. The principal reason, which impedes us to determine the missing IDs, is the unavailability of the topology (edges) of Tanner graph, which relates the unique IDs and sub-groups. In this paper, we add graph edge information to RF tags' memory in addition to group IDs and its unique ID. By doing this, message passing decoding [14] in wireless communications can be applied to identify the unique IDs of missing objects.

The example scenario of this extended group coding enabling us "Missing Object Identification" is shown in Fig.1. There are grouped objects on a pallet. Some objects may be missing from the group, so the operator must check the integrity of the group. When all RF tags belonging to the group are verified to exist, the operator can let the pallet go. On the other hand, when it is found that some objects are missing from the group, the group verification system alerts the operator and executes another round of RF tag inventory

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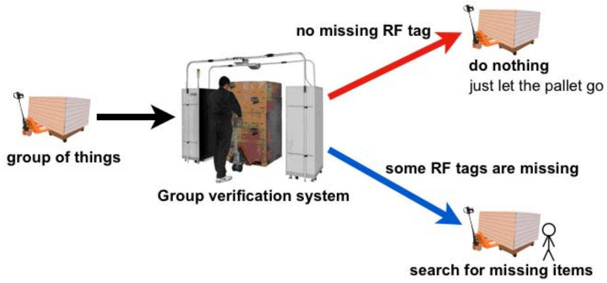

Fig. 1. Example usage scenario of missing object identification

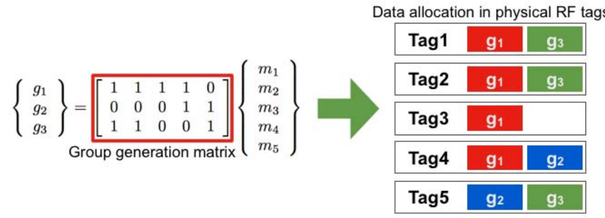

Fig. 2. Example of a group represented by multiple group IDs

particularly targeting the missing IDs. If the retrial inventory fails to detect the missing objects, the group verification system reports the missing IDs to the operator. The whole process up to this point does not require network connection nor the interaction with EDI system.

This paper is organized as follows. In Section II, we revisit the original group coding for the completeness of the paper. In Section III, extended group coding is introduced. In Section IV, we introduce the evaluation of extended group coding with a numerical simulation and an experimental evaluation. Section V concludes this paper.

II. Review of the Original Group Coding

When we check the integrity of a group with the original group coding, the unique IDs and group-related information are extracted and processed to determine the number of missing objects from the group. The brief introduction of the original group coding is as follows.

- The group coding checks the integrity of a group with the check sum technique. The check sum of a group is calculated as the bit-by-bit XOR (exclusive or) of all hashes of RF tags' unique IDs belonging to the group, and the group coding system writes the check sum to these RF tags' memory. This check sum also has a role as an identifier of the group, it means we can judge whether an RF tag belongs to the group or not by reading its memory, so we call it "group ID". When some RF tags are missing from the group, we can detect it because the recalculated group ID becomes different from the group ID written in identified RF tags' memory.
- Using multiple sub-groups' group IDs to represent one group, group coding can determine the number of RF tags missing from the group. This method is expressed by a matrix equation, and the following equation shows the structure of a group which is represented by n group IDs and contains m RF tags.

$$\begin{Bmatrix} g_1 \\ \vdots \\ g_n \end{Bmatrix} = \begin{bmatrix} G \end{bmatrix} \begin{Bmatrix} m_1 \\ \vdots \\ m_m \end{Bmatrix} \tag{1}$$

In this equation, m_x and g_x represent the hash of x'th RF tag's unique ID and the x'th sub-group's group ID, respectively. G is an m-column, n-row matrix composed of 0 and 1. We call this matrix "group generation matrix" because it defines the structure of the whole group. Each group ID calculated by this equation is recorded by the RF tags which belong to that group (Fig.2). We named this procedure "group encoding".

- When some RF tags are missing from this group, Eq.1 changes to the following equation.

$$\begin{Bmatrix} g_c \\ \hline g_e \end{Bmatrix} = \left[\begin{array}{c|c} G_{cr} & G_{cm} \\ \hline G_{er} & G_{em} \end{array} \right] \begin{Bmatrix} m_r \\ \hline m_m \end{Bmatrix} \tag{2}$$

In this equation, g_c and g_e represent the array of group IDs of sub-groups which preserve their integrity and that of the group IDs of sub-groups which lose their integrity, respectively. m_r and m_m represent the array of hashes of RF tags identified by the interrogator and that of hashes of RF tags missing from the group, respectively. The group generation matrix G is decomposed into four partial matrices, G_{cr}, G_{er}, G_{cm} and G_{em}, in accordance with these four arrays, g_c, g_e, m_r and m_m. In these terms, g_c, g_e, G_{cr}, G_{er} and m_r are known because identified RF tags remember these information. G_{cm} represents the contribution of missing RF tags onto the correct group IDs (g_c), which can be zero if we choose proper hash. Therefore, G_{em} and m_m are only unknown terms, but the product of these terms can be calculated by the following equation.

$$G_{em} m_m = g_e \oplus G_{er} m_r. \tag{3}$$

Because $G_{em} m_m$ is an array of linear combinations of RF tags' hashes missing from the group, the number of missing RF tags can be calculated as the rank of $G_{em} m_m$. We named this procedure "group decoding".

In the previous paper by the authors [13], we introduced this group coding method, and its validity was confirmed by the numerical simulation and the experimental evaluation.

III. Extended Group Coding Scheme

In this section, we introduce extended group coding. We explain the procedure to create a group as "group encoding" and the procedure to determine missing unique IDs as "group decoding" in the following sub-sections.

A. Group encoding in the extended scheme

Similar to the original group coding, the extended group coding use a group generation matrix to calculate group IDs. The entire group is logically split into mutually overlapped

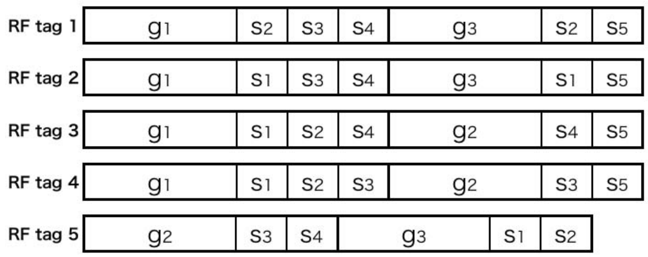

Fig. 3. Example of the information recorded in RF tags belonging to a group of 5 objects

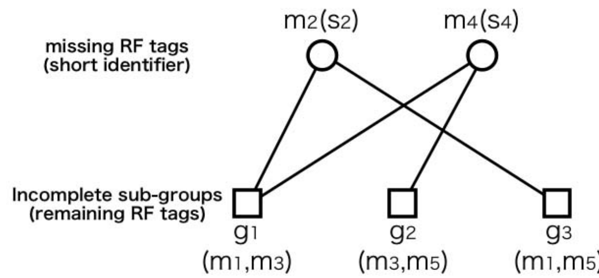

Fig. 4. Graph expression of retrieved relationship between missing RF tags and sub-groups

sub-groups. The group generation matrix describes the Tanner graph of the sub-group and unique IDs. Group IDs are calculated by bit-by-bit XOR of unique IDs which we want to retrieve, so the bit-length of one group ID is the same as the bit-length of unique ID which we want to retrieve. We presume the length of unique IDs are consistent in a group.

In addition to the group ID, the extended group coding assigns "short ID" to all RF tags belonging to a group. Each RF tag in a sub-group records the group ID of this sub-group and the short IDs of other RF tags belonging to this sub-group. Note that the short ID of its own is not required to be stored in its memory. Since these short IDs are used to re-establish the Tanner graph of the group, short IDs are required to be unique only within the group. Accordingly, the bit-length of a short ID can be shorter than that of the unique ID which we want to retrieve. For example, 8-bit short IDs are generally enough to distinguish less than 255 RF tags. Since these short IDs do not have to be recalculated in the group decoding procedure, any data, for example a portion of factory programmed Tag ID [15], can be used as the short IDs. This combination of a group ID and short IDs is a set of the information required of each RF tag to record per sub-group. Each RF tag must record as many sets of information as the number of sub-groups which it belongs.

For example, suppose a group containing 5 RF tags. There are 3 sub-groups to represent the whole group. Sub-group 1 contains RF tag 1, 2, 3 and 4, sub-group 2 contains RF tag 3, 4 and 5, and sub-group 3 contains RF tag 1, 2 and 5. g_x represents the x'th sub-group's group ID and s_x represents the short ID of x'th RF tag in this example. In this group, RF tag 1 records the information combination of sub-group 1, g_1, s_2, s_3 and s_4, and that of sub-group 3, g_3, s_2 and s_5, and RF tag 1 does not record its own short ID which is s_1. Likewise, other RF tags also records the information of sub-groups which they belong to. All the information recorded in these RF tags in this example is shown in Fig.3.

The procedure of the group encoding in this extension can be summarized as follows.

1) The interrogator collects unique IDs of all RF tags belonging to the group.
2) The group coding system generates a group generation matrix and calculates each group IDs.
3) The group coding system computes a short ID for each RF tag.
4) Each group ID and related short IDs are written in the memory of RF tags which belong to the sub-groups.

B. Group decoding in the extended scheme

The group decoding in the extended group coding starts with the integrity-check of each sub-group by its group ID. The information of each incomplete sub-group, which is composed of the linear combination of missing RF tags' unique IDs and short IDs of each missing RF tag, is collected. The linear combination of the unique IDs of RF tags missing from each sub-group can be calculated as the XOR of the sub-group's group ID and the unique IDs of the all identified RF tags belonging to the sub-group just like the $G_{em}m_m$ in Eq.2. The short IDs of RF tags missing from each sub-group are recorded by all the identified RF tags belonging to the sub-group.

To determine the unique IDs of missing RF tags, the group coding system must retrieve the matrix G_{em} in Eq.2, which is the partial matrix of the group generation matrix and shows the structure of combination of missing unique IDs. G_{em} can be retrieved from the information of short IDs of RF tags missing from each sub-group. For example, suppose that RF tag 2 and 4 are missing from the group shown in Fig.3. From the information collected from identified RF tag 1, 3 and 5, the following information about missing RF tags is retrieved.

- Two RF tags whose short IDs are s_2 and s_4 are missing from the group.
- The missing RF tag whose short ID is s_2 belongs to sub-group 1 and 3.
- The missing RF tag whose short ID is s_4 belongs to sub-group 1 and 2.

Figure 4 shows a graph expression of these information. This graph is a bipartite graph composed of a set of nodes representing missing RF tags and a set of nodes representing incomplete sub-groups. Each "missing RF tag node" is connected, by a single edge, to "incomplete sub-group nodes" which it belongs to. The meaning of this graph structure is just equivalent to that of G_{em}, the relationship between missing RF tags and incomplete sub-groups, so this information can be expressed by the following equation.

$$\left\{ \begin{array}{c} g_1 \oplus m_1 \oplus m_3 \\ g_2 \oplus m_3 \oplus m_5 \\ g_3 \oplus m_1 \oplus m_5 \end{array} \right\} = \left[\begin{array}{cc} 1 & 1 \\ 0 & 1 \\ 1 & 0 \end{array} \right] \left\{ \begin{array}{c} m_2 \\ m_4 \end{array} \right\} \tag{4}$$

The left side of this equation is the $G_{em}m_m$, the array of linear combinations of missing RF tags' unique IDs, and the unknown terms in this equation are only m_2 and m_4, the unique IDs of missing RF tag 2 and 4. In this case, these terms can be calculated as $g_3 \oplus m_1 \oplus m_5$ and $g_2 \oplus m_3 \oplus m_5$, respectively.

The procedure of the group decoding in this extension can be summarized as follows.

1) The interrogator collects unique IDs of RF tags and group-related information recorded by these RF tags.
2) The group coding system checks the integrity of each sub-group using its group ID and identified RF tags' unique IDs. If there is no sub-group which lost its integrity, there is no missing RF tag, and the group decoding is completed.
3) If there are some sub-groups which lost their integrity, the group coding system collects the information of these incomplete sub-groups. Collected information of each incomplete sub-group is composed of the linear combination of the unique IDs of RF tags missing from the sub-group and the short IDs of these RF tags.
4) The group coding system retrieves the matrix G_{em} in Eq.2 from missing RF tags' short IDs of each incomplete sub-groups.
5) Using retrieved G_{em} and $G_{em}m_m$, the group coding system calculates each element of m_m, missing RF tag's unique ID.

The whole decoding process can be alternatively interpreted as a message passing decoder. The group decoding also starts with the integrity-check of each sub-group by its group ID. Let us take a case where RF tag 2 and 4 are missing from the group shown in Fig.3 as an example. Figure 5 shows the iterative decoding method. The initial Tanner graph can be established as shown in (1) in Fig.5 where the missing IDs are represented by filled circles. Thin and thick lines indicate un-identified and identified edges, respectively. Collected variables (unique IDs) are passed to factors (group IDs) as in (2) to recover missing unique IDs (m_2 and m_4) as shown in (3). In process (3), the destination of factor passing are determined by short IDs. The second variable passing shown in (4) verifies that the recovered unique IDs satisfy the parity check of g_1.

IV. Evaluation

A. Numerical simulation on the determination accuracy

We evaluate the missing object identification performance of the proposed method with a numerical simulation. The procedure of the simulation is as follows.

1) The simulator prepares 100 virtual RF tags. Each RF tag has 96-bit EPC generated randomly as the unique ID.
2) The simulator applies the group encoding procedure in the extended scheme introduced in Section III to these 100 RF tags. The group generation matrix is generated like a generation matrix of LDPC [16]. The number of RF tags which each sub-group contains is fixed at 4, and the number of sub-groups which each RF tag belongs to is given by a variable number j which varies from 2 to 7, as shown in Table I. The 8-bit serial number generated by the group coding system is used as a short ID of each RF tag. Since a set of the information needed to be recorded to an RF tag for a subgroup is 120-bit (96-bit group ID and three short IDs of the other RF tags in the subgroup), the bit-length of group's information recorded by each RF tag is $120j$-bit. It is expected that the performance of the determination increases by increasing the number of sub-groups which each RF tag belongs to.
3) The simulator removes n RF tags randomly from the group. n varies from 1 to 99.
4) The simulator applies the group decoding procedure in the extended scheme to $(100 - n)$ identified RF tags to determine the unique IDs of missing RF tags. If there is any difference between the result of the group decoding and the unique IDs of RF tags actually missing, it is counted as an error.
5) The simulator repeats the above procedure 10000 times for each j and n, and calculates error rate, which is the number of the errors occurred in 10000 trials, for each pattern.

TABLE I
THE CONDITIONS OF GROUP GENERATION MATRIX IN THE NUMERICAL SIMULATION

Condition	Value
Number of RF tags which each sub-group contains	4
Number of sub-groups which each RF tag belongs to	2-7 (variable j)

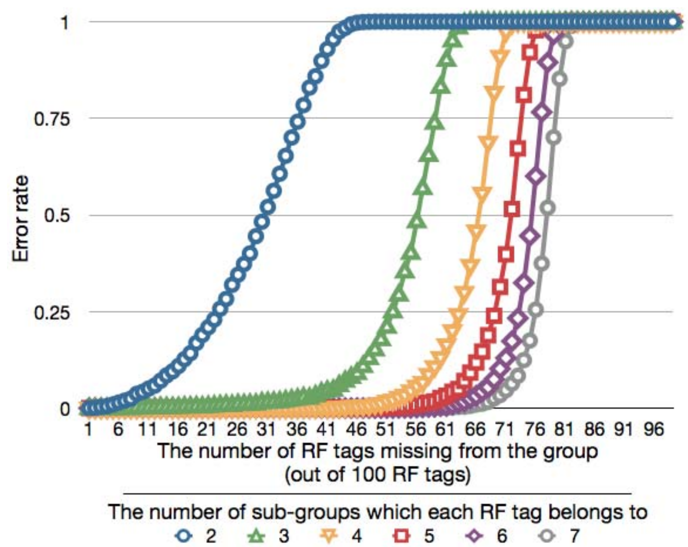

Fig. 6. Error rate of the determination of missing RF tags' unique IDs by the group decoding

Figure 6 shows the result of the simulation. From this chart, it is clear that the performance of the determination increases by increasing the number of sub-groups which each RF tag belongs to. Figure 7 shows the maximum number of RF tags which can be determined by the group coding within the

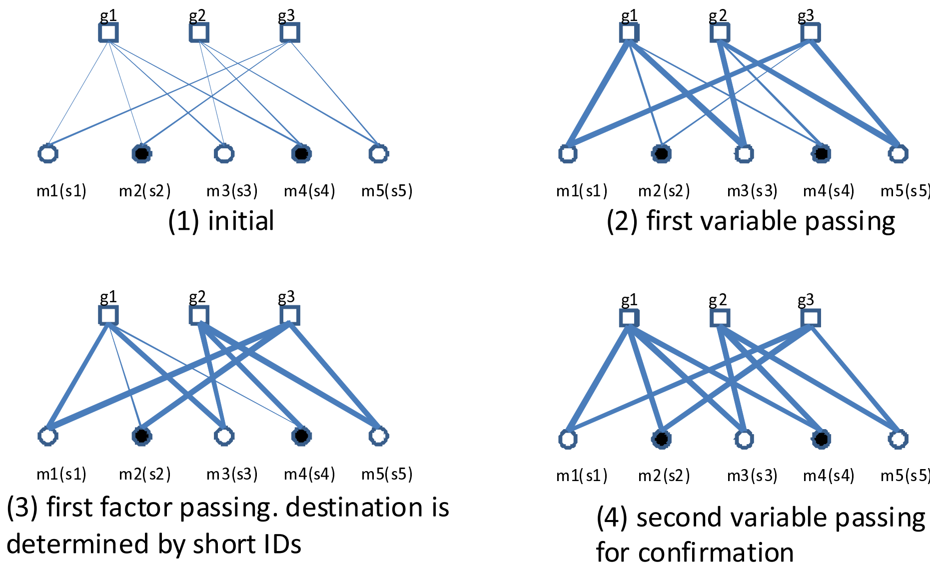

Fig. 5. Example of the iterative decoding procedure

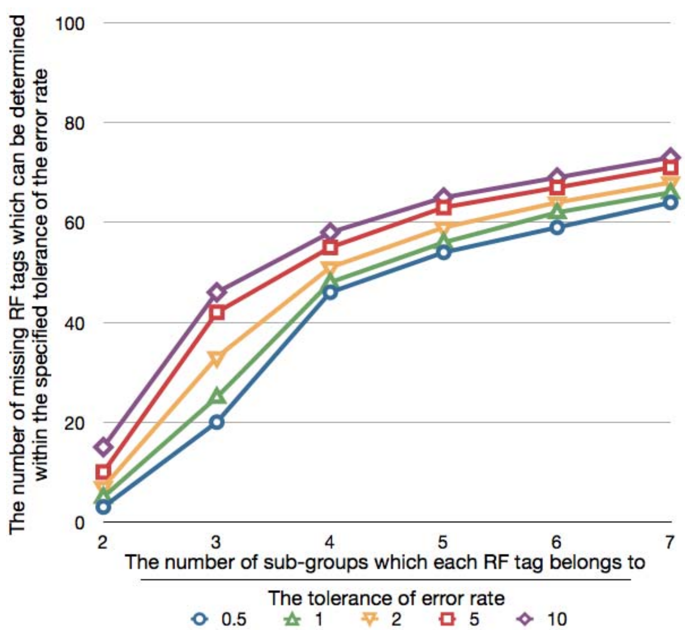

Fig. 7. The maximum number of RF tags which can be determined within the specified error rate

Fig. 8. KU-U1610 RFID interrogator

several specified error rates, and this number also increases when we increase the number of sub-groups which each RF tag belongs to. For example, when each RF tag belongs to 4 sub-groups and records 480-bit additional information, the group coding system can determine up to 46 missing RF tags' unique IDs within 0.5% error rate. On the other hand, with 7 sub-groups for each RF tag, which means each RF tag records 840-bit information, the unique IDs of 64 missing RF tags can be determined within the same error rate. These results agree to the afore-mentioned expectation that the performance of the determination increases when increasing the amount of group-related information.

B. Experimental evaluation

We implemented the proposed scheme on an RFID system. We used an UHF-band RFID interrogator KU-U1610 (Fig.8) provided by Panasonic System Networks Co., Ltd, which conforms to EPCglobal UHF C1G2 air protocol. In our implementation, the interrogator handles the access to RF tags. The computation of the group encoding and decoding is computed on the laptop PC connected to the interrogator. The program of the computation is written in Java.

With this implementation, we evaluate the missing object identification performance. The procedure of the experiment is as follows.

1) We prepare 20 physical RF tags whose unique IDs are generated randomly. These RF tags are positioned in front of the antennas connected to the interrogator as shown in Fig.9.

Fig. 9. The environment of the experiment

2) We apply the group encoding procedure in the extended scheme to these RF tags. We examined $j = 3$ case and $j = 7$ case, and other conditions of group generation matrix are the same as those of the afore-mentioned numerical simulation. In this experiment, 16-bit hashes of RF tags' unique IDs are used to calculate group IDs, which means that each 16-bit hash is treated as the unique ID of each RF tag, so a set of the information about one sub-group has 40-bit length (16-bit group ID and three 8-bit short IDs). Therefore, each RF tag records 120-bit and 280-bit group-related information in $j = 3$ case and $j = 7$ case, respectively.
3) We remove n RF tags from the group and apply the group decoding procedure in the extended scheme to identified $(20 - n)$ RF tags. Then, we compare the result of the group decoding and the hashes of physically missing RF tags' unique IDs. We examined three cases, $n = 4$, $n = 8$ and $n = 12$.
4) We repeat the above procedure 10 times for each j and n to calculate the actual error rate of the determination for each pattern.

The performance of the proposed scheme against 20 RF tags is revealed by an additional numerical simulation and the result is shown in Fig.10. We compared the result of the numerical simulation and that of the experiment.

The results of the experiment of $j = 3$ case and $j = 7$ case are shown in Fig.11 and Fig.12, respectively. In these charts, the line shows the result of the numerical simulation, and filled circles represent the result of this experiment. Because the number of trials for each pattern is small, there is a slight difference between the result of the numerical simulation and that of the experiment in $j = 3$ case, and there is no discernible difference between them. In $j = 7$ case, there is no difference between the result of the numerical simulation and that of the experiment. In this experiment, the time duration of the computation of the group coding is also measured. It is revealed from the measurement that the computation of the group encoding and decoding procedure takes about 0.1 second and 0.2 second, respectively. These duration are negligible in the whole process including the access to the RF tags. Therefore, it is confirmed from these results that the proposed scheme works well on the real RFID system.

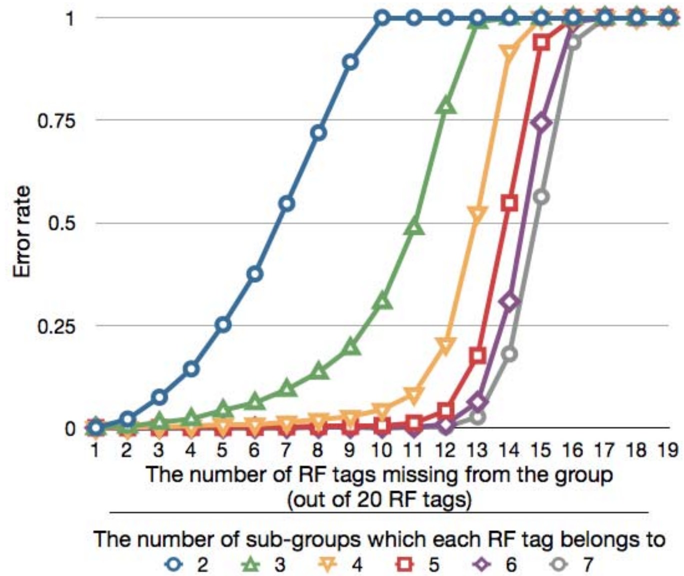

Fig. 10. Error rate of the determination of missing RF tags' unique IDs by the group decoding (against 20 RF tags)

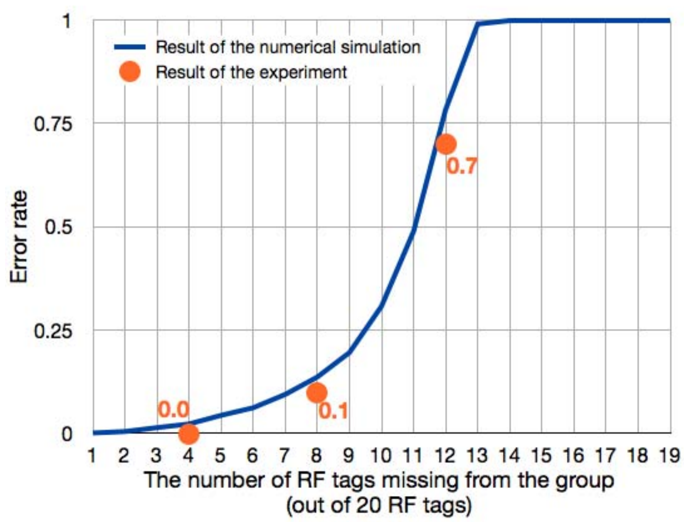

Fig. 11. The result of the experiment ($j = 3$)

V. Conclusion

Missing object identification with group coding of RF tags explores a new horizon of RFID. Even when there is no network connection, we can identify missing objects. This enables the automated first screening in shipment inspections and thus speeds up the business process. The group coding of RF tags logically splits the target group into mutually overlapped sub-groups. The proposed method writes the graph topology of each RF tag and sub-groups into RF tags' memory in addition to group ID. Group decoding can be done by an iterative decoding method by using short IDs. Numerical simulation reveals that the proposed scheme can identify up to 64 missing RF tags' 96-bit unique IDs out of 100 RF tags

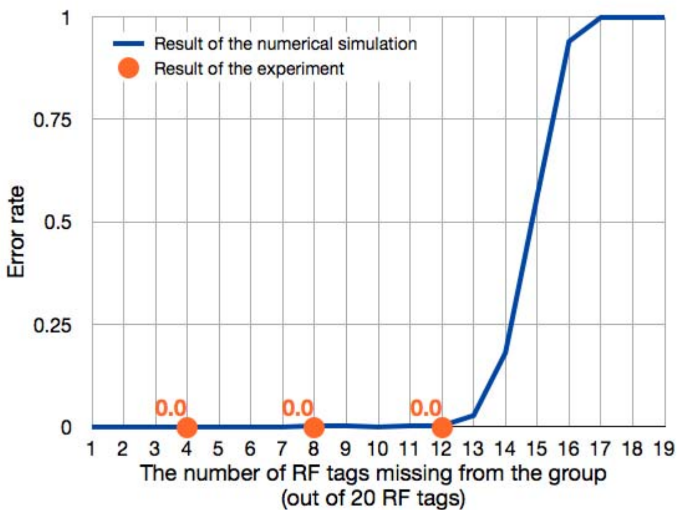

Fig. 12. The result of the experiment ($j = 7$)

by writing 840-bit group-related information to each RF tags. Experimental evaluation is also performed with a group of 20 RF tags. Measured accuracy of the determination of 12 missing RF tags are 30% and 100% with 120-bit and 280-bit RF tag memory consumption, respectively. This accuracy agrees well with the numerical simulation.

Acknowledgements

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